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(54) **Plasma processing method and apparatus for carrying out the same.**

(57) A plasma processing method and an apparatus for carrying out the method are disclosed in which a processing gas is introduced into a processing chamber (10, 25, 50), and a periodically amplitude- or frequency-modulated high-frequency voltage is applied to plasma generating means (13, 14; 28, 29; 56, 48), to generate a discharge plasma and to carry out predetermined processing by the plasma.

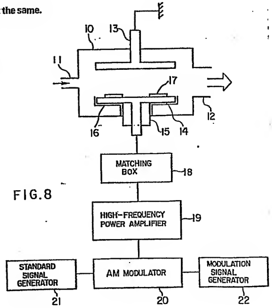

FIG.8

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PLASMA PROCESSING METHOD AND APPARATUS FOR CARRYING OUT THE SAME

The present invention relates to a plasma processing method suitable for the fabrication of semiconductor devices, and to an apparatus for carrying out the plasma processing method.

The plasma processing is carried out, for example, in such a manner that a processing gas is introduced into an evacuated processing chamber, and then a plasma is generated by applying a high-frequency voltage between parallel plate electrodes, to carry out desired processing. The processing carried out as above includes the dry etching in which an ion or radical produced from the processing gas by the plasma etches a film in accordance with a pattern formed by a resist film, the plasma chemical vapor deposition in which the processing gas is decomposed by the plasma to deposit a film on a substrate, and the plasma polymerization in which the processing gas is polymerized by the plasma to deposit a film on a substrate.

Recently, in order to enhance the degree of integration in a semiconductor device and to reduce the cost of a solar cell, these plasma processing techniques have been widely used in fabrication processes. Further, in order to improve the production yield, high-level processing characteristics are now required. For example, in the dry etching, it is required to increase the etching rate, thereby enhancing the productivity, to make large the selectivity

(that is, a ratio of the etching rate for a desired film to the etching rate for a layer underlying the film), thereby improving the production, yield, and to etch a semiconductor layer so as to form a fine pattern with satisfactory accuracy.

In the conventional plasma processing, the etching characteristics and the characteristics of deposited film have been controlled by changing the kind, pressure and flow rate of the processing gas, and the high-frequency power for generating the plasma.

However, satisfactory characteristics have not been obtained by controlling such factors. For example, the dry etching encounters the following problems.

Firstly, when the pressure of the processing gas is made high, the selection ratio is improved, but the etching accuracy is lowered.

Secondly, when the high-frequency power is increased, the etching rate becomes high, but the selectivity is reduced.

It is an object of the present invention to provide a plasma processing method in which all of plasma processing characteristics such as the film deposition rate, film quality, etching rate, selectivity and etching accuracy are improved. In the conventional plasma processing method, the film deposition rate conflicts with the film quality, and the etching rate, selectivity and etching accuracy conflict with each other. Further, it is another object of the present invention is to provide an apparatus for carrying

out such a plasma processing method.

In order to attain the above objects, according to the present invention, a high-frequency voltage having a frequency of more than 10^2 Hz (preferably, of the order of 1 MHz) for generating a plasma is periodically modulated to control ion energy distribution and/or electron temperature distribution, thereby adjusting the amount and kind of each of the ion and radical formed in the plasma. Thus, one of the etching rate, selectivity and etching accuracy is remarkably improved in an etching process without making smaller the remaining ones of these factors, as compared with a conventional etching process, and further either the film deposition rate or the film quality is improved in a film deposition process.

It is preferred that the modulation frequency lies in a range from 10 to 10,000 Hz. For the reason that the amplitude modulation is easy to control, the amplitude modulation is superior to the frequency modulation. In the amplitude modulation, it is most desirable to change the amplitude of the high-frequency voltage stepwise, since a processing condition can be readily set. That is, the desired processing condition can be readily obtained by making the optimum combination of a repetition period $(t_1 + t_2)$ of the modulation, a ratio t_1/t_2, and an amplitude ratio V_3/V_2, where t_1 indicates a period when the high-frequency voltage has a small amplitude V_2, and t_2 a period when the voltage has a large amplitude V_3.

The above and other objects, features and

advantages of the present invention will be apparent from the following detailed description of the preferred embodiments of the invention taken in conjunction with the accompanying drawings, in which:

Fig. 1 is a graph showing the ion energy distribution in the conventional plasma processing using parallel plate electrodes;

Fig. 2 is a waveform chart showing a high-frequency voltage used in the conventional plasma processing;

Fig. 3 is a waveform chart showing an example of an amplitude-modulated high-frequency voltage according to the present invention;

Fig. 4 is a graph showing the ion energy distribution obtained when the amplitude-modulated high-frequency voltage of Fig. 3 is used;

Fig. 5 is a waveform chart showing an example of a frequency-modulated high-frequency voltage according to the present invention;

Fig. 6 is a graph for comparing etching characteristics according to the present invention will those in the conventional plasma etching;

Fig. 7 is a waveform chart showing an amplitude-modulated high-frequency voltage according to the present invention for etching a silicon oxide film;

Fig. 8 is a block diagram showing an embodiment of an apparatus for carrying out plasma processing (hereinafter referred to as a "plasma processing apparatus"), according to the present invention, of which embodiment is

of the amplitude modulation type;

Fig. 9 is a block diagram showing another embodiment of a plasma processing apparatus according to the present invention, of which embodiment is of the frequency modulation type;

Fig. 10 is a block diagram showing an example of a device for generating a frequency-modulated signal;

Fig. 11 is a block diagram showing a further embodiment of a plasma processing apparatus according to the present invention, of which embodiment is of the electron cyclotron resonance type;

Fig. 12 is a block diagram showing still another embodiment of a plasma processing apparatus according to the present invention;

Fig. 13 is a waveform chart showing an amplitude-modulated output of the magnetron shown in Fig. 12;

Fig. 14 is a block diagram showing still a further embodiment of a plasma processing apparatus according to the present invention;

Fig. 15 is a waveform chart showing an example of a voltage applied to the grid electrode shown in Fig. 14,

Figs. 16A and 16B are schematic sectional views for a process of etching an $A\ell$ film; and

Figs. 17A and 17B are schematic sectional views for a process of etching an oxide film.

Prior to explaining a plasma processing method and a plasma processing apparatus according to the present invention, a conventional plasma etching method will be

explained below.

In the conventional dry etching method in which a high-frequency voltage having a frequency of 0.5 to 20 MHz (for example, 13.56 MHz) is applied between parallel plate electrodes, the ion energy distribution and electron temperature distribution are determined by the gas pressure and high-frequency power. When an aluminum film 70 is etched to form a wiring pattern as shown in Figs. 16A and 16B, a high-energy ion is not required for etching the aluminum film 70, but is necessary for etching a phosphosilicate glass film 71 or silicon layer 72 underlying the aluminum film 70. Accordingly, the selectivity (a ratio of the etching rate for the aluminum film to the etching rate for the underlying material) can be enhanced by reducing the ion energy.

However, a high-energy ion is indispensable for removing an aluminum oxide film 73 on aluminum surface and for forming a side wall 75 which makes it possible to etch the aluminum film pattern with high accuracy. The side wall 75 is formed of a polymerized-material film or deposited film, and can prevent the side etching caused by a carbon-containing gas which is generated by bombarding a resist film 74 with an ion.

Fig. 1 schematically shows the ion energy distribution in a conventional plasma etching method.

Referring to Fig. 1, the ion lying in a region A is indispensable for the removal of the aluminum oxide film and the formation of the side wall, and a large amount of

ion lying in a region B adjacent to the region A would etch an underlying material. Accordingly, it is impossible to make the selectivity sufficiently large.

In order to solve this problem, according to the present invention, an amplitude-modulated high-frequency voltage shown in Fig. 3 is used in place of a conventional high-frequency voltage shown in Fig. 2.

Now, a plasma processing method according to the present invention which uses an amplitude-modulated high-frequency voltage, will be explained below, with reference to Fig. 3. In this method, a gas pressure is made higher, as compared with the conventional plasma processing method. Further, a high-frequency voltage V_2 lower than the conventional voltage V_1 (shown in Fig. 2) is applied between electrodes for a period t_1, as shown in Fig. 3. Since the gas pressure is high, the ion energy at the period t_1 is low, but the discharge current is increased at this period. Accordingly, the energy of an electron flowing from each electrode to a plasma is lowered, but the number of such electrons is increased. Thus, the production of a radical which contributes to etching, is also increased.

At a period t_2, a high-frequency voltage V_3 higher than the conventional voltage V_1 is applied between the electrodes, under a high gas pressure. Thus, ion energy necessary for removing the aluminum oxide film and for forming the side wall is obtained. The ion energy distribution in the above case is schematically shown in Fig. 4.

Referring to Fig. 4, a large amount of low-

energy ion or radical is generated by the discharge at the period t_1, as indicated by a curve D. Thus, the etching rate is increased. While, a high-energy ion is generated by the discharge at the period t_2, as indicated by a curve C. The amount and energy of the high-energy ion can be controlled by changing a ratio t_1/t_2 and the voltage V_3. (Preferably, the ratio t_1/t_2 is put in a range of about 1 to 20, and a ratio V_3/V_2 is put in a range of about 1.2 to 4.) The ion quantity and ion energy indicated by the curve C can be decreased to the irreducible minimum, in the above manner.

In the above, explanation has been made on the case where a high-frequency voltage is amplitude-modulated. However, the same effect as in this case, can be obtained in the case where a high-frequency voltage is frequency-modulated as shown in Fig. 5. Referring to Fig. 5, a high-frequency voltage having a frequency of 13.56 MHz at a period t_3 is frequency-modulated at a period t_4 so as to have a frequency of 1 MHz. Thus, at the period t_4, the discharge voltage becomes higher, and the ion energy is increased. It is to be noted that the frequency modulation is hard to control.

Fig. 6 shows etching characteristics obtained by a plasma etching method according to the present invention which uses the amplitude-modulated high-frequency shown in Fig. 3, and etching characteristics obtained by a conventional plasma etching method. As is apparent from Fig. 6, the plasma etching method according to the present invention

is far superior to the conventional plasma etching method.

Next, as shown in Figs. 17A and 17B, another example of plasma etching, that is, the case where a silicon oxide film 76 on a silicon wafer 72 is etched, will be explained below. In order not to advance the etching for the silicon wafer 72 after the etching for the silicon oxide film 76 has been completed, it is desirable to make the difference between the etching speed for the silicon oxide film and the etching speed for silicon, as large as possible. When compared with the silicon oxide film 76, silicon 72 is etched by a low-energy ion. Accordingly, in order to enhance the selectivity, that is, a ratio of the etching rate for the silicon oxide film 76 to the etching rate for silicon 72, the ion for etching is required to have energy greater than a value necessary for etching the silicon oxide film 76. The ion energy can be enhanced either by lowering the gas pressure or by increasing the high-frequency power supplied to the plasma.

However, when the gas pressure is lowered, the ion energy is enhanced, but the ionization efficiency is lowered, which reduces the etching rate. When the high-frequency power is increased, not only the ion energy is enhanced, but also the amount of heat generated by ion bombardment is increased. Thus, the temperature of the wafer is elevated.

When a pattern is formed in a wafer for a semiconductor device, a resist pattern 74 is formed on the wafer before an etching process. The resist film 74 softens at a

temperature of about 120°C or more, and thus the resist pattern 74 is deformed, which makes it impossible to etch the pattern in wafer with high accuracy. In some cases, there arises a problem that the resist film changes in quality and it becomes impossible to completely remove the resist film after the etching process.

According to the present invention, as shown in Fig. 7, a high-frequency voltage V_4 higher than the conventional high-frequency voltage is applied for a period of t_5 sec., and the amplitude of the voltage V_4 is reduced for a period of t_6 sec. That is, an amplitude-modulated high-frequency voltage is used. It is to be noted that the averaged amplitude of the high-frequency voltage V_4 at a period of $(t_5 + t_6)$ sec. is made substantially equal to the constant amplitude of the conventional high-frequency voltage.

As mentioned previously, the ion energy for etching a silicon oxide film 76 is higher than the ion energy for etching silicon 72. In order to make large the etching rate and selectivity, it is required that the ion energy is distributed in a range higher than a level necessary for etching the silicon oxide film 76.

In a discharge according to the present invention, the high-frequency voltage V_4 has a large amplitude at the period t_5 so that a high-energy ion is incident on the wafer, and has a small amplitude at the period t_6 so that the ion energy is smaller than a level necessary for etching silicon 72.

Since the high-frequency power supplied by the voltage V_4 having such a waveform is equvalent to the conventional high-frequency power, the resist film 74 never softens. In other words, the ion energy is distributed in a high energy range, without softening the resist film formed on the wafer. Thus, the etching rate can be made 2.5 times as large as the conventional etching rate, and the selectivity can be made 1.8 times as large as the conventional selectivity. Besides the present method is applied to etching for gate wiring, a multilayer resist fim and a single crystal silicon, etc.

In the above, the plasma etching has been explained. However, the present invention can exhibit a similar effect in the plasma chemical vapor deposition or plasma polymerization. The characteristics of a film deposited by the above techniques are dependent upon the electron temperature in the plasma, the energy of ion incident on a substrate, and the ion and radical produced in the vicinity of an ion sheath. The electron temperature distribution in the plasma, the kind of each of the ion and radical produced in the plasma, and the ratio between the amount of the ion and the amount of the radical, can be controlled by modulating a high-frequency voltage in the same manner as having been explained with respect to the plasma etching. Accordingly, when conditions for depositing a film having excellent characteristics are known, the discharge plasma is controlled by a modulated high-frequency voltage according to the present invention so that the above

conditions are satisfied. Thus, the processing characteristics with respect to the film deposition can be improved.

In the above explanation, a high-frequency voltage having a frequency of 13.56 MHz has been used. However, the frequency of the high-frequency voltage is not limited to the above value, but may be other values capable of generating and maintaining a discharge.

The modulation frequency is made far smaller than a plasma processing time of 1 to tens of min., that is, may be such that the plasma processing can be stopped at a desired time without making any difference in processing condition. In view of the above, the frequency of a high-frequency voltage is put in a range exceeding 10^2 Hz (that is, the frequency is made equal to, for example, 13.56 MHz, 27.12 MHz, 54.24 MHz and so on, and a frequency of 2.45 GHz is used when a microwave plasma is formed), and the modulation frequency is put in a range exceeding 10 Hz (preferably, in a range of about 10 Hz to 10 KHz).

In the above, the plasma etching, plasma chemical vapor deposition and plasma polymerization which use parallel plate electrodes, have been explained. However, the present invention is not limited to such construction, but is applicable to the plasma processing using an external electrode of capacitance coupling or inductance coupling type and the plasma processing utilizing a plasma generated by a microwave and the electron cyclotron resonance. In these cases, although no electrode exists in a processing chamber, the high-frequency or microwave power supplied to

a plasma is controlled to control the electron temperature distribution in the plasma, thereby adjusting the kind and amount of each of the ion and radical produced in the plasma. Thus, various characteristics of plasma processing can be controlled.

Further, in the above explanation, the high-frequency power supplied to a plasma is modulated with a rectangular wave. However, the modulation waveform is not limited to the rectangular wave. In other words, when a desired ion energy distribution, a desired electron temperature distribution, and a desired ratio between the amount of the desired ion and the amount of the desired radical, are known, the modulation waveform is determined in accordance with these factors. The use of a rectangular wave as the modulation waveform has an advantage that a processing condition can be readily set and the plasma processing can be readily controlled.

Now, explanation will be made on embodiments of a plasma processing apparatus for carrying out the above-mentioned plasma processing method.

Fig. 8 shows, in block, an embodiment of a plasma processing apparatus according to the present invention, of which embodiment is of the cathode coupling type and is used for etching an aluminum film or silicon oxide film by means of an amplitude-modulated discharge.

Referring to Fig. 8, a processing chamber 10 is provided with a gas inlet 11 for introducing a processing gas into the chamber 10, and a gas outlet 12. Further, an

earth electrode (namely, a grounded electrode) 13 and a high-frequency electrode 14 are disposed in the processing chamber 10. The high-frequency electrode 14 is fixed to the wall of the chamber 10 through an insulating bushing 15, and a shield case 16 for preventing the discharge between the electrode 14 and the inner surface of the chamber 10 is provided around the electrode 14. The high-frequency electrode 14 is connected to a high-frequency power amplifier 19 through a matching box 18. A signal having a frequency of 13.56 MHz from a standard signal generator 21 is amplitude-modulated by an amplitude modulator 20 in accordance with a signal from a modulation signal generator 22, and then applied to the high-frequency power amplifier 19.

The modulation signal generator 22 can generate various waveforms such as a rectangular wave and a sinusoidal wave, and moreover can change the period and amplitude of such waveforms. It is to be noted that since the rectangular wave modulates the signal from the standard signal generator 21 in a discrete fashion, the rectangular wave can readily set the processing condition, as compared with the sinusoidal wave and the compound wave of it.

The modulation signal generator 22 generates a modulation signal for modulating the signal having a frequency of 13.56 MHz from the standard signal generator 21 in accordance with predetermined plasma processing so that an amplitude-modulated signal such as shown in Fig. 3 or 7 is obtained. The amplitude-modulated signal thus obtained

is applied to the high-frequency power amplifier 19. A signal having a waveform such as shown in Fig. 3 or 7 is delivered from the high-frequency power amplifier 19, and applied to the electrode 14 through the matching box 18. Since the amplitude-modulated signal is applied to the amplifier 19, the frequency of the output signal of the amplifier 19 is kept constant. Accordingly, desired matching can be made for the output signal of the amplifier 19 by the matching box 18 for 13.56 MHz.

As can be seen from the above, the present embodiment can generate a discharge plasma which has been explained in the plasma processing method according to the present invention, and thus can carry out satisfactory plasma processing.

A plasma processing apparatus of the anode coupling type for carrying out the plasma etching and plasma chemical vapor deposition can be realized by exchanging the positions of the earth electrode 13 and electrode 14 shown in Fig. 8.

Fig. 9 shows another embodiment of a plasma processing apparatus according to the present invention, of which embodiment is of the anode coupling type and uses a frequency-modulated high-frequency signal.

Referring to Fig. 9, a processing chamber 25 is provided with a gas inlet 26 for introducing a processing gas into the chamber 25, and a gas outlet 27. Further, an electrode 28 provided with an insulating bushing 30 and a shield case 31 is disposed in an upper part of the processing

chamber 25, and an earth electrode 29 is disposed in a lower part of the chamber 25.

A wafer 32 is placed on the earth electrode 29, and the electrode 28 is connected to a high-frequency power amplifier 35 through a matching box 33 for 13.56 MHz and a matching box 34 for 1 MHz which are connected in parallel.

A signal having a frequency of 13.56 MHz from a standard signal generator 37 is modulated by a frequency modulator 36 so as to include a signal part having a frequency of 13.56 MHz and a signal part having a frequency of 1 MHz, in accordance with a signal from a modulation signal generator 38. A ratio of the signal part having a frequency of 13.56 MHz to the signal part having a frequency of 1 MHz can be freely set by the modulation signal. The frequency-modulated signal from the modulator 36 is amplified by the power amplifier 35. Then, the signal part having a frequency of 13.56 MHz is sent to the electrode 28 through the matching box 33 for 13.56 MHz, and the signal part having a frequency of 1 MHz is sent to the electrode 28 through the matching box 34 for 1 MHz. Thus, a modulated high-frequency discharge is generated between the electrodes 28 and 29, and the plasma processing can be performed.

In the present embodiment, the frequency-modulated high-frequency signal is generated by the frequency modulator 36. However, the generation of the frequency-modulated signal is not limited to the above method, but such a signal may be produced by a device shown in Fig. 10.

Referring to Fig. 10, a high-frequency signal from

a standard signal generator 40 is applied to frequency dividers 41 different, in demultiplication factor form each other, and the outputs of the frequency dividers are individually varied by attenuators 42. The outputs of the attenuators 42 are applied to an adder 43, to obtain a signal having a plurality of frequencies. In the case where an appropriate number of frequency dividers 41 are provided and the frequency dividers are connected to the attenuator 42 in one-to-one correspondence, the device shown in Fig. 10 can produce substantially the same signal as do the frequency modulator 36 and the amplitude modulator 20.

In the case where parallel plate electordes are provided in a processing chamber as shown in Figs. 8 and 9, the high-frequency voltage applied between the electrodes has a function of generating a discharge for putting the processing gas in a plasma state, and another function of accelerating an ion formed in the plasma.

Next, explanation will be made on the case where discharge means for producing a plasma and acceleration means for accelerating an ion in the plasma can be separately provided.

Fig. 11 shows a further embodiment of a plasma processing apparatus according to the present invention, of which embodiment is of the electron cyclotron resonance type.

Referring to Fig. 11, a signal having a frequency of 2.45 GHz from a standard signal generator 44 is modulated by an amplitude modulator 45 in accordance with a signal from a modulation signal generator 46. The signal

thus modulated is amplified by a power amplifier 47, and then applied to a magnetron 56 which is mounted on an end portion of a waveguide 48, to be converted into a microwave. The amplitude-modulated microwave passes through the waveguide 48, and is then introduced into a processing chamber 50 bounded by a quartz wall. Coils 49 and 50 each for generating a magnetic field are provided around the processing chamber 50. A plasma is generated by the resonance of the electron motion with the microwave and magnetic field. At this time, the electron energy depends upon the intensity of the microwave introduced into the chamber 50. Accordingly, the electron temperature distribution can be controlled by the above modulation. Thus, the kind and amount of each of the ion and radical produced in the plasma, can be adjusted by the modulation. Accordingly, it is possible to control the etching characteristics of a plasma etching apparatus of the electron cyclotron resonance type, and to control the quality of a film formed by a plasma chemical vapor deposition apparatus of the electron cyclotron resonance type. Incidentally, in Fig. 11, reference numeral 54 designates a gas feed pipe for introducing a processing gas into the processing chamber 50, 55 an exhaust pipe, 52 a stage, and 55 a substrate.

Fig. 12 shows still another embodiment of a plasma processing apparatus according to the present invention.

Referring to Fig. 12, a waveguide 48 and a magnet 49 are provided around a processing chamber 50, and a magnetron 56 mounted on an end portion of the waveguide 48

is connected to a driving power source 44 and a control power source 46 which serves as discharge modulating means. A high-frequency voltage from a signal generator 59 is applied to a stage 52 which is disposed in the processing chamber 50, through a high-frequency amplifier 58 and a matching box 57. Further, a gas feed pipe 55 from processing gas supply means (not shown) and an exhaust pipe 55 from evacuating means (not shown) are connected to the processing chamber 50. In order to generate a plasma in the processing chamber 50, a predetermined amount of processing gas is introduced into the chamber 50 through the gas feed pipe 54, while evacuating the chamber 50 through the exhaust pipe 55. Thus, the pressure of the chamber 50 is kept at a predetermined value within a range from 1 x 10^{-4} to 10 Torr. When the magnetron 56 is operated with the driving power source 44 in the above state, a microwave generated by the magnetron 56 passes through the waveguide 48 and is introduced into the processing chamber 50. In the chamber 50, the electron cyclotron resonance is caused by the microwave thus introduced and a magnetic field formed by the magnet 49. Thus, an intense plasma is generated in the processing chamber 50.

At this time, the output of the magnetron 56 can be amplitude-modulated with a control signal from the control power source 46, as shown in Fig. 13. In a period B_1 when the microwave has an amplitude A_1, the field intensity in the plasma is strong, and an electron makes a high-speed cyclotron motion. Thus, the electron temperature is

elevated. While, in a period B_2 when the microwave has an amplitude A_2, the above field intensity is weak, and an electron makes a low-speed cyclotron motion. Thus, the electron temperature is lowered. Accordingly, the electron temperature distribution can be freely controlled by changing the amplitudes A_1 and A_2 and a ratio of the period B_1 to the period B_2.

Now, let us suppose that an ion C and a radical D are required for the plasma processing. A high electron temperature is necessary for generating the ion C, and the radical D is produced at a low electron temperature. Accordingly, the ion C and radical D can be produced in the plasma in an optimum state, by setting the amplitude A_1 to a value suitable for generating the ion C, by setting the amplitude A_2 to a value suitable for producing the radical D, and by setting the periods B_1 and B_2 in accordance with a desired ratio between the amount of ion C and the amount of the radical D.

Further, such a signal as shown in Fig. 13 is generated by the signal generator 59, and then applied to the stage 52 through the high-frequency amplifier 58 and matching box 57. Thus, the ion in the plasma is accelerated in accordance with the amplitude of the signal applied to the stage 52, and then impinges on a wafer 53. In the period B_1 when the output signal of the signal generator 59 has the amplitude A_1, the ion is accelerated by a strong electric field, and the ion energy becomes large. While, in the period B_2 when the above output signal has the

amplitude A_2, the ion accelerating electric field is weak, and therefore the ion energy is small. That is, the ion energy can be controlled by the amplitudes A_1 and A_2. Further, a ratio of the amount of high-energy ion to the amount of low-energy ion can be controlled by changing a ratio of the period B_1 to the period B_2. In other words, the ion energy distribution can be controlled by the amplitude-modulated high-frequency signal delivered from the signal generator 59.

In the present embodiment, two amplitudes A_1 and A_2 and two periods B_1 and B_2 have been used. However, the present invention is not limited to such a case, each of the amplitude and period can take various values to obtain a high-frequency signal which is amplitude-modulated in a desired manner.

Fig. 14 shows still a further embodiment of a plasma processing apparatus according to the present invention. The present embodiment is different from the embodiment shown in Fig. 12, in that a grid electrode 60 is used as the ion accelerating means. In the present embodiment, a signal generator 62 generates a D.C. signal having an A.C. component superposed thereon, that is, a signal having a waveform such as shown in Fig. 15. It is to be noted that the output signal of the signal generator 62 is not limited to the waveform shown in Fig. 15, but can take various waveforms.

The output signal of the signal generator 62 is amplified by a power amplifier 61 so as to have an

amplitude of 100 to 1,000 V, and then applied to the grid electrode 60. Accordingly, in a period t_1 when the signal applied to the grid electrode 60 has a voltage V_1, the plasma ion drawn out of the processing chamber 60 is accelerated by a strong electric field, and thus a high-energy ion impinges on the wafer 53. While, in a period t_2 when the above signal has a voltage V_2 (smaller than V_1), a low-energy ion impinges on the wafer 53. Accordingly, the amount of the high-energy ion and the amount of the low-energy ion can be controlled by changing the application period t_1 of the voltage V_1 and the application period t_2 of the voltage V_2, respectively. Generally speaking, the energy distribution of plasma ion incident on the wafer can be freely controlled by changing the waveform of the signal applied to the grid electrode 60.

In the above, explanation has been made on the case where the generation of plasma and the acceleration of ion are separately controlled in a plasma processing apparatus using microwave discharge. However, it is needless to say that the plasma generation and ion acceleration can be separately controlled in a plasma processing apparatus using high-frequency discharge different from the microwave discharge.

In the above embodiments, the microwave or high-frequency signal has two amplitudes after amplitude modulation, as shown in Fig. 13. However, the present invention is not limited to such a case, but the above signal can take three or more amplitudes to make optimum the composition of

plasma and to obtain the optimum ion energy distribution.

Further, it is not always required to amplitude-modulate the above signal, but the signal may be frequency-modulated as shown in Figs. 9 and 10. Since the frequency-modulated, high-frequency or microwave signal can control plasma characteristics and ion energy distribution, the frequency modulation can produce the same effect as the amplitude modulation.

In the foregoing, a plasma processing method according to the present invention and the embodiments of a plasma processing apparatus according to the present invention have been explained. It can be readily seen from the foregoing explanation that the present invention is applicable to all processing methods and apparatuses which utilize a plasma.

As has been explained in the foregoing, according to the present invention, the ion energy distribution (corresponding to the accelerated state of ion generated in a plasma) and the electron temperature distribution in the plasma (corresponding to the discharge state for producing the plasma) are controlled to adjust the kind and amount of each of the ion and radical produced in the plasma, thereby improving the plasma processing. That is, in the plasma etching, one of the etching rate, selectivity and etching accuracy can be remarkably improved. In the film deposition, one of the deposition rate and film quality can be improved. Further, a plasma processing apparatus according to the present invention is provided with discharge

modulating means. Accordingly, the electron temperature distribution is controlled to adjust the kind and amount of each of the ion and radical produced in the plasma, therefore the characteristics of the plasma processing can be improved.

Further, some of plasma processing apparatuses according to the present invention include means for modulating a voltage applied between a plasma and a stage for supporting a wafer. Accordingly, the energy distribution of ion incident on the wafer can be controlled, and therefore the characteristics of the plasma processing are further improved.

CLAIMS:

1. A plasma processing method comprising the steps of:

introducing a processing gas into a processing chamber (10, 25, 50); and

applying a periodically-modulated high-frequency voltage to plasma generating means (13, 14; 28, 29; 56, 48), to generate a plasma and to carry out predetermined processing by said plasma.

2. A plasma processing method according to Claim 1, wherein said high-frequency voltage is modulated at an interval for shorter than an etching time, and predetermined etching is carried out for said etching time.

3. A plasma processing method according to Claim 1, wherein said high-frequency voltage is amplitude-modulated.

4. A plasma processing method according to Claim 1 used for etching a metal or oxide film of a body which includes an underlying material, said metal or oxide film formed on said underlying material, and a resist pattern formed on said metal or oxide film.

5. A plasma processing apparatus comprising:

gas introducing means (11, 26, 54) for introducing a processing gas into a processing chamber (10, 25, 50);

means (20, 21, 22; 36, 37, 38; 40, 41, 42, 43; 44, 45, 46) for generating a periodically-modulated high-frequency voltage; and

plasma generating means (13, 14; 28, 29; 56, 48) receiving said periodically-modulated high-frequency voltage

for generating a plasma in said processing chamber.

6. A plasma processing apparatus according to Claim 5, wherein said periodically-modulated high-frequency voltage is an amplitude-modulated voltage.

7. A plasma processing apparatus according to Claim 6, wherein said amplitude-modulated high-frequency voltage has a rectangular waveform.

8. A plasma processing apparatus according to Claim 7, wherein the modulation frequency of said amplitude-modulated high-frequency voltage lies in a range from 10 to 10,000 Hz.

9. A plasma processing apparatus according to Claim 8, wherein said amplitude-modulated high-frequency voltage has a large amplitude V_3 for a period t_2 and has a small amplitude V_2 for a period t_1, and wherein a ratio t_1/t_2 is substantially put in a range from 1 to 20, and a ratio V_3/V_2 is substantially put in a range from 1.2 to 4.

10. A plasma processing apparatus according to any one of Claims 5 through 9, wherein said plasma generating means is formed of parallel plate electrodes (13, 14; 28, 29).

11. A plasma processing apparatus comprising:

gas introducing means (11, 26, 54) for introducing a processing gas into a processing chamber (10, 25, 50);

discharge means (13, 14; 28, 29; 56, 48) for putting said processing gas in a plasma state;

discharge voltage modulating means (20; 36; 41, 42; 45; 46) connected to said discharge means;

ion accelerating means (52, 60) for accelerating an ion produced in a plasma, to cause the accelerated ion to impinge on a body to be processed; and

control means (59, 62) connected to said ion accelerating means for controlling a voltage applied to said ion accelerating means.

12. A plasma processing apparatus according to Claim 11, wherein said discharge voltage modulating means is amplitude modulating means.

13. A plasma processing apparatus according to Claim 12, wherein said control means includes modulation means.

14. A plasma processing apparatus according to Claim 13, wherein said modulation means of said control means is amplitude modulating means.

15. A plasma processing apparatus according to Claim 11, wherein said discharge means puts said processing gas in said plasma state on the basis of the electron cyclotron resonance caused by a microwave and a magnetic field.

16. A plasma processing apparatus according to Claim 15, wherein said ion accelerating means is a grid electrode (60) applied with a D.C. voltage having an A.C. component superposed thereon.

17. A plasma processing apparatus according to Claim 15, wherein said discharge voltage modulating means is amplitude modulating means.

FIG. I
PRIOR ART

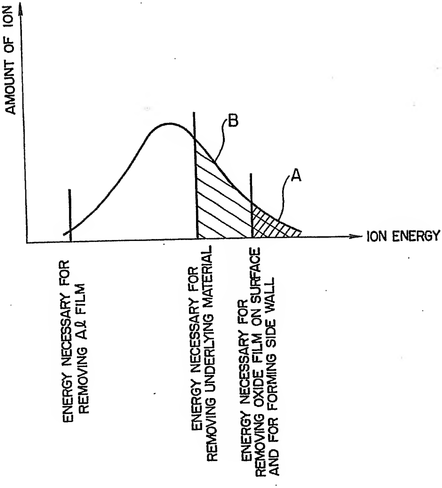

FIG. 2
PRIOR ART

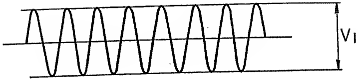

FIG. 3

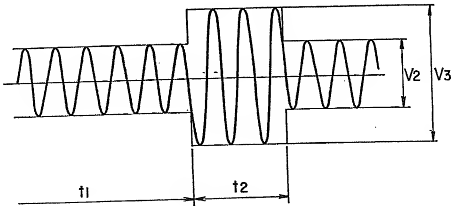

FIG.4

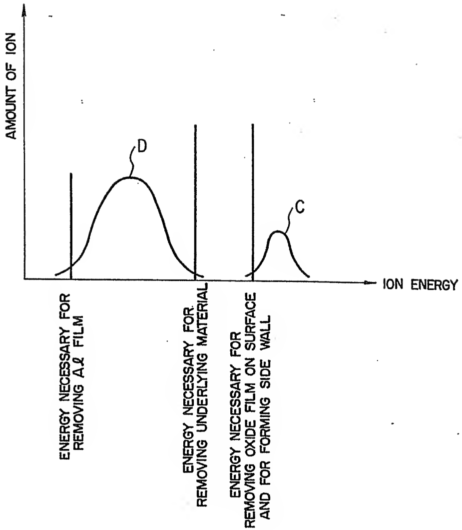
AMOUNT OF ION
D
C
ION ENERGY
ENERGY NECESSARY FOR REMOVING Aℓ FILM
ENERGY NECESSARY FOR REMOVING UNDERLYING MATERIAL
ENERGY NECESSARY FOR REMOVING OXIDE FILM ON SURFACE AND FOR FORMING SIDE WALL

FIG.5

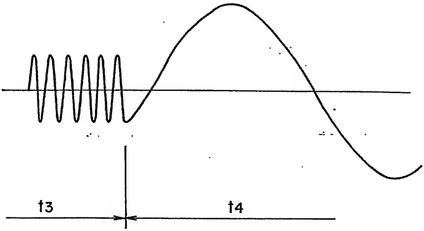

FIG.7

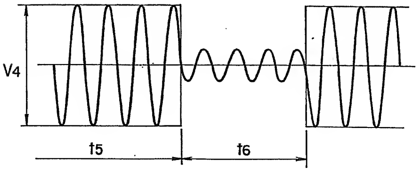

FIG.6

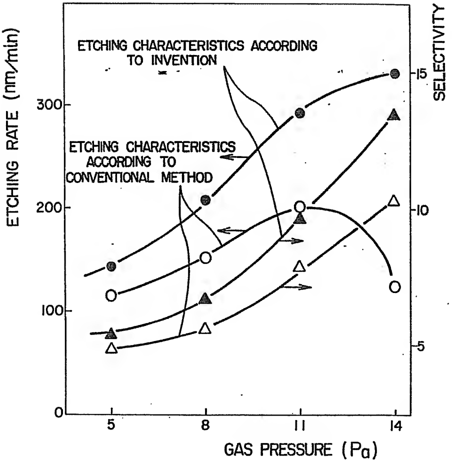
ETCHING CHARACTERISTICS ACCORDING TO INVENTION
ETCHING CHARACTERISTICS ACCORDING TO CONVENTIONAL METHOD
ETCHING RATE (nm/min)
SELECTIVITY
GAS PRESSURE (Pa)
0
100
200
300
5
8
11
14
5
10
15

FIG.8

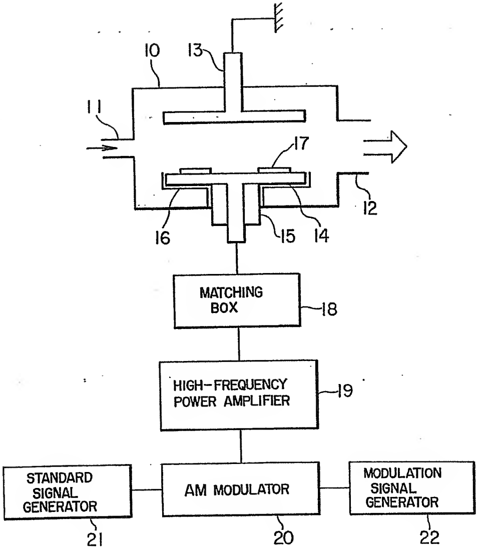
10
13
11
17
12
16
15
14
MATCHING BOX
18
HIGH-FREQUENCY POWER AMPLIFIER
19
STANDARD SIGNAL GENERATOR
AM MODULATOR
MODULATION SIGNAL GENERATOR
21
20
22

FIG.9

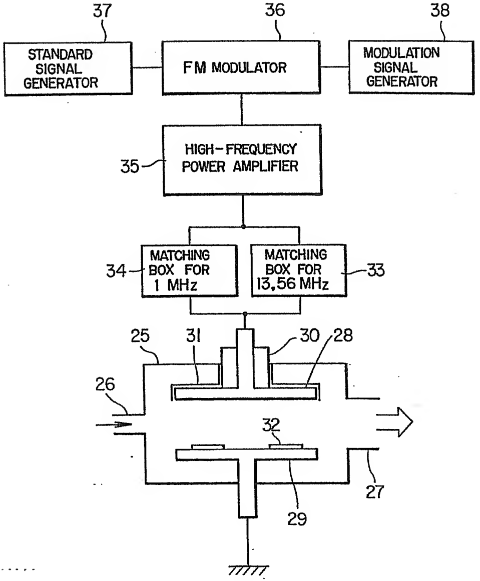
37
36
38
STANDARD SIGNAL GENERATOR
FM MODULATOR
MODULATION SIGNAL GENERATOR
HIGH-FREQUENCY POWER AMPLIFIER
35
MATCHING BOX FOR 1 MHz
MATCHING BOX FOR 13.56 MHz
34
33
25
31
30
28
26
32
27
29

FIG.10

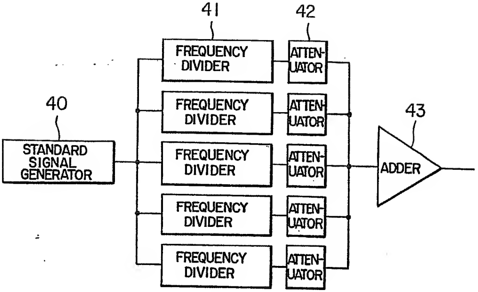
41
42
FREQUENCY DIVIDER
ATTEN-UATOR
FREQUENCY DIVIDER
ATTEN-UATOR
40
43
STANDARD SIGNAL GENERATOR
FREQUENCY DIVIDER
ATTEN-UATOR
ADDER
FREQUENCY DIVIDER
ATTEN-UATOR
FREQUENCY DIVIDER
ATTEN-UATOR

FIG.11

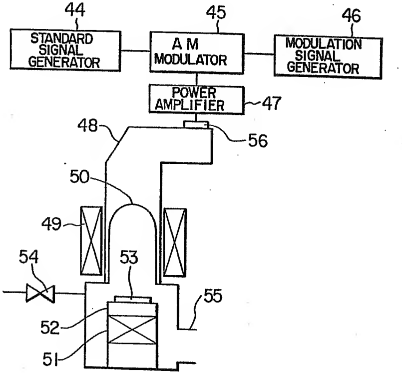
44
45
46
STANDARD SIGNAL GENERATOR
A M MODULATOR
MODULATION SIGNAL GENERATOR
POWER AMPLIFIER
47
48
56
50
49
54
53
55
52
51

FIG. 12

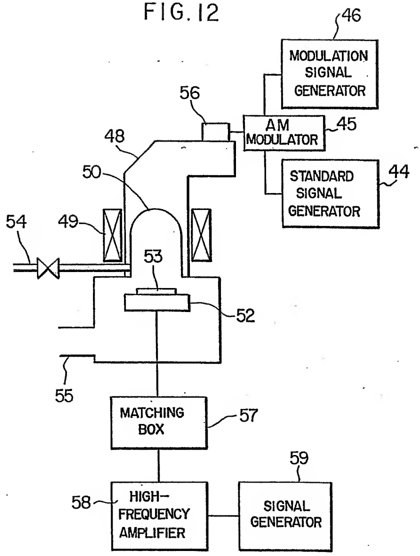
46
MODULATION SIGNAL GENERATOR
56
AM MODULATOR
45
48
STANDARD SIGNAL GENERATOR
44
50
54
49
53
52
55
MATCHING BOX
57
59
58
HIGH-FREQUENCY AMPLIFIER
SIGNAL GENERATOR

FIG.13

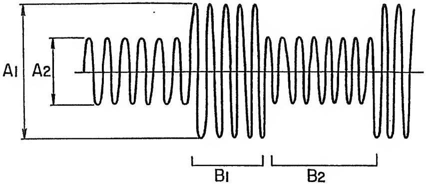

FIG. 14

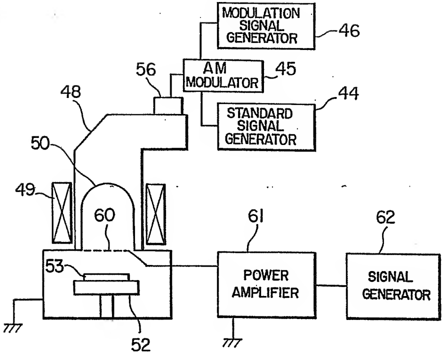
MODULATION SIGNAL GENERATOR
46
AM MODULATOR
45
56
48
44
STANDARD SIGNAL GENERATOR
50
49
60
61
62
53
POWER AMPLIFIER
SIGNAL GENERATOR
52

FIG. 15

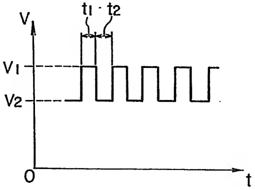
V
t1
t2
V1
V2
0
t

FIG. 16A

BEFORE ETCHING

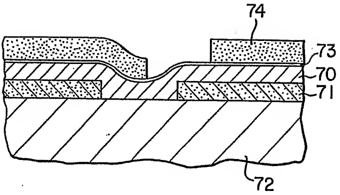

FIG. 16B

AFTER ETCHING

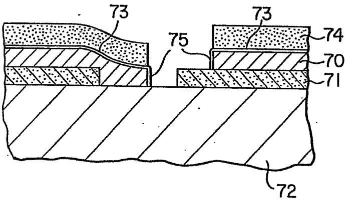

FIG. 17A

BEFORE ETCHING

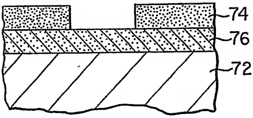

FIG. 17B

AFTER ETCHING